Chapter 5
Development of a Robot-Assisted Surgery System for Cranio-Maxillofacial Surgery

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Abstract Medical robots have been developed rapidly in recent years. Clinical application of da Vinci system showed its advantages. Currently, there is no specialized robot system for cranio-maxillofcial surgery. We developed a cranio-maxillofacial surgical robot system focusing on the reconstruction of mandibular defects.

With the funding of the Chinese National High Technology Research and Development Program (863 Program), we developed a computer-aided design (CAD) system for four typical operations: reconstruction of mandibular defects, orbit reconstruction, skull base tumor resection, and orthognathic surgery, a navigation system and a robot with three arms for mandibular reconstruction. In the CAD system, the operation pattern was designed based on surgeons' habits and experiences. The software system was easy to be used with many functions for designing different surgical procedures. In surgical navigation system for guiding the robot, the hardware of the navigation system was assembled, and the software system of real-time registration was realized. The robot was designed and assembled. It had three arms and was able to finish the bone graft placement precisely and automatically under the navigation guidance according to the preoperative design. The whole system was assessed by model and animal experiment with good results.

Keywords Robot • Cranio-maxillofacial surgery • Navigation

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5.1 General Information of Surgical Robots

Surgical robots have been tried in many fields of surgery like in orthopedics, microsurgery, neurosurgery, ENT surgery, catheterization procedure, etc. The first robot assisting orthopedic operations was made by Integrated Surgical System Company, called ROBODOC system, in 1992 [1, 2]. It was developed from industry robots and was able to perform operations like knee joint replacement. Since then the other robots assisting surgery were developed, but very few of them could be used in clinic. In August of 2015, a newly developed robot by a research team in Beijing was used to assist spine surgery in a real patient and got satisfactory result. Currently the commercially available surgical robot is da Vinci surgical robot which helped in finishing prostatectomy for the first time in the University of Frankfurt in 2000 and has become the main and much welcome surgical robot in the world. So far, as we know, there is no specially designed surgical robot for cranio-maxillofacial (CMF) surgery [3–6]. We began to develop our system in 2010 and have made two robots: one for mandibular reconstruction and the other for needle insertion to diagnose and treat lesions in the skull base. In this chapter we introduce the first robot system.

Our robot-assisted surgery (RAS) system for CMF surgery consisted of the following three parts: computer-aided design (CAD) system for CMF surgery, surgical robot for CMF surgery, and medical experiment for the CAD and robot. The outlines of RAS system for CMF surgery is showed in Fig. 5.1.

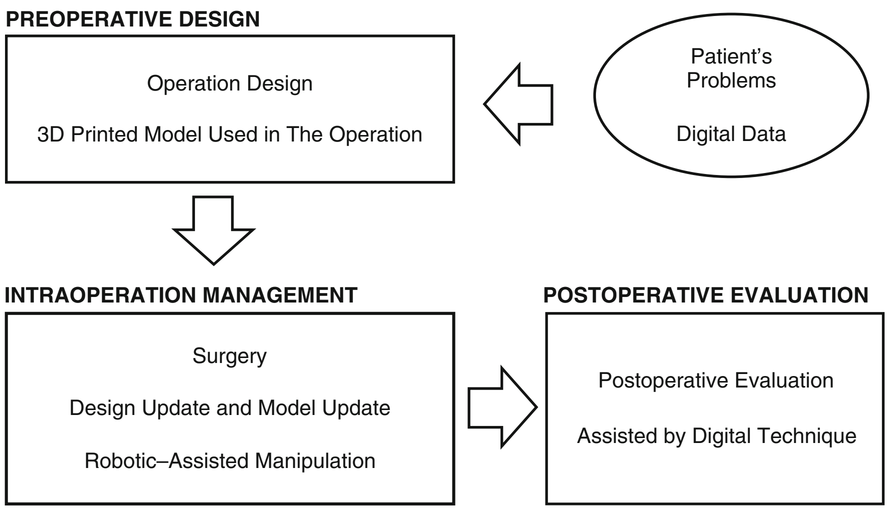

Fig. 5.1 The outlines of RAS system for CMF surgery

5.2 Computer-Aided Design (CAD) System for CMF Surgery

The CAD was designed for four typical and more or less difficult operations: orthognathic surgery, reconstruction of the orbital defects, resection of skull base tumors, and reconstruction of mandibular defects. It has the following five main functions: volume rendering of medical images, segmentation on medical images, CT/MRI image fusion, craniofacial database service, and virtual surgery designing.

The software is easy to use with good interactive regulation of transfer function. It can produce high-quality volume rendering of medical images and get quick and precise segmentation of soft tissue tumors based on graph-cut algorithm. Abstracted tumor from CT data can be visualized three dimensionally and measured for its volume with 99.5 % agreement of the true volume of the tumor. GPU marching cubes algorithm was used to build highly precise three-dimensional reconstruction of bony structures of the skeleton from CT images. The CT/MRI image fusion is another character of the CAD; it well fuses the bony structures abstracted from CT with the vessels abstracted from MRI and creates a new image with more information for more precise medical image analysis and treatment planning. It can also fuse other images obtained by the other image equipments, like fusion of CT data with 3D laser scan image data for the dentition.

We also built a CMF database with more than 20,000 CT data of CMF to assist preoperative design. Currently, one of its functions we already used in clinic is to search for “similar skull.” We selected 71 landmarks on the CMF bones. Based on the landmarks, it can retrieve “similar skull” in a few seconds.

With the above mentioned basic functions, the CAD performs its most important task: carrying virtual surgery design for different operations, mainly for orthognathic surgical management, mandibular reconstruction, orbital reconstruction, and removal of the skull base tumors. The designing system is easy to be learned and used for virtual surgical planning step by step. All procedures can be stored and repeated, which helps young surgeons to learn how to design and do these operations. After the virtual planning is done, 3D stereolithographic model (STL model) can be manufactured from the virtual planning model by using rapid prototyping technique for model surgery. Or the virtual planning data is inputted into the navigation system to guide surgeons or robots to perform operations according to the virtual preoperative plan. Thus the precise real-time registration of the CAD system with navigation system is the key point for realization of accurate navigation.

5.3 Surgical Robot for CMF Surgery

The development of the robot had the following main contents: conformation of robotic system, control system, safety control of the robotic system, navigation and trail program, and test of the robot.

5.3.1 *Conformation of the Robotic System*

The robot had three arms and six degrees of freedom, its hold strength was 30–50 N, and its working square was $200 \times 200 \times 200$ mm. Each arm consisted of two segments and three joints. Figure 5.2 shows the mechanical structure of the robot and the appearance of the robot after assembling.

5.3.2 *Safety Control of the Robotic System*

Safety is the first consideration for clinical application of medical robots. It was reported that more than 60 % of adverse events in clinical use were caused by robots' malfunction. Our robot safety control involved the workflow from patients' diagnosis, virtual surgical planning, navigation to robot assisting surgery, robotic system itself like essential electro-circuit for safety control, interactive process, and

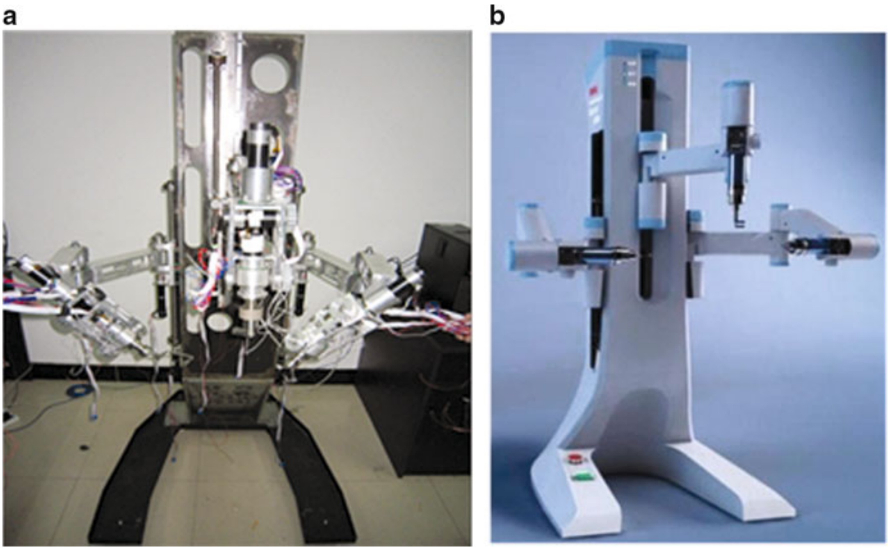

Fig. 5.2 (**a**) The mechanical structure of the robot. (**b**) The appearance of the robot

recovery mechanisms when unexpected faults occur. With these measures, patient safety and operator safety can be guaranteed.

5.3.3 Navigation and Trail Program

Navigation was realized by coordinate switch of four coordinates: 3D object space, image coordinate {V}; physical space, patient coordinate {P}; robotic space, robotic coordinate {R}; and optical space, optical coordinate {M}. The algorithms of trail program included cube polynomial and quintic polynomial.

After all these works were completed, the whole system of the robot was packaged. It consists of the robot, optical tracker, and workstation.

5.3.4 Test of the Robot

We assessed positioning accuracy of the robot and found its repeat positioning error was less than 0.10 mm and the systemic absolute positioning error <2.45 mm, which met the requirement of the design indicators for performance check. And the robot was ready for medical experiment.

5.4 Medical Experiment for the Robotic System

5.4.1 Evaluation of the CAD Software

Twenty-five young oral and maxillofacial surgeons were asked to use and evaluate the CAD software. The satisfaction degree was 91 %.

5.4.2 Accuracy of the Three-Dimensional Reconstruction of the CAD Software

The accuracy of three-dimensional reconstruction and the accuracy of the navigation system and the robot were all tested by model or animal study.

Thirty model skulls were used to test the accuracy of the three-dimensional reconstruction of the CAD software. Titanium screws of 0.1 mm were fixed on the models. The marked models were CT scanned. Reconstruction of the models was performed on the CT data. The comparative study between the reconstructed models and the real models showed that the error was 0.21 mm.

Fig. 5.3 Making osteotomy on the mandible under navigation

5.4.3 Accuracy of the Navigation System

For navigation assessment, the flowchart of the animal experiment includes the following: (1) use living goats as study animal, (2) fix marks on the cranio-maxillofacial region, (3) have CT scan, (4) have virtual surgical design, (5) do operation under navigation, (6) have postoperative CT scan, and (7) compare pre- and postoperative results. All of the four typical operations were tested for navigation accuracy. Comparison of postoperative results with preoperative design showed that the error of mandibular reconstruction was 2.9 mm, error of orthognathic surgery 2.7 mm, error of orbital reconstruction 1.2 mm, and error of skull base surgery 1.8 mm. There are many factors that can affect the accuracy of navigation. These factors are CT scan slice thickness, resolution and radiation dosage, shadow of titanium plates, accuracy of three-dimensional reconstruction, titanium plate bending, movements of remaining bone segments, etc. Current animal study results are acceptable for clinical application.

5.4.4 Animal Experiment of Robot-Assisted Operations

The experimental flow was similar to the abovementioned navigation study. After the animal CT data were collected, the preoperative design was planned using the CAD system. The robot and animal registration was performed, the surgery of making osteotomy on the mandible was done, and the fibular bone graft was fabricated under navigation according the preoperative design (Fig. 5.3). When the mandibular defect was made, the robots' two side arms held two remaining bone segments, the

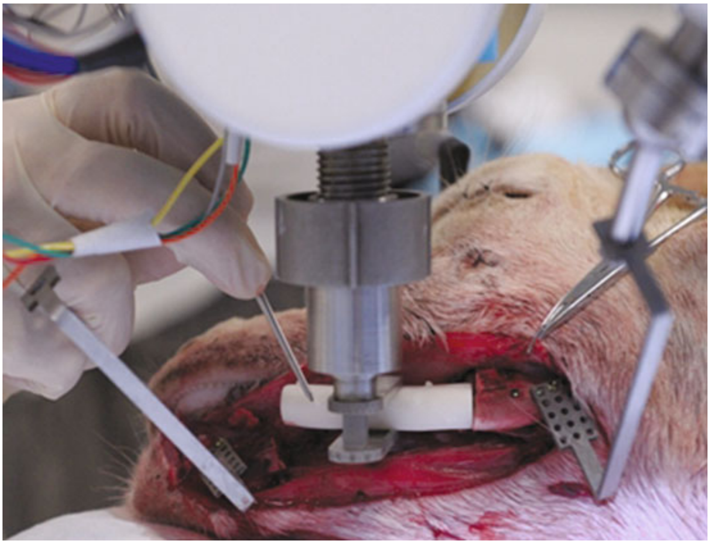

Fig. 5.4 The middle arm carried the bone graft automatically to the defect

middle arm held the bone graft, and under navigation the middle arm carried the bone graft automatically to the defect (Fig. 5.4). After the bone graft was positioned, it was fixed with titanium plates. Comparison of postoperative results with preoperative design showed that errors of left, right, and middle arms were 1.15 mm, 2.68 mm, 2.175 mm, respectively.

The robot animal study showed that the robot can move smoothly and do accurate placement of bone graft and aid fixation. Its three arms can coordinate well to aid bone graft placement for different types of mandibular defects. Its flexibility, bone holding method, miniaturization, etc. need improvement for higher stability and accuracy.

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